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CHAPTER 3

Innovations in the En Route Care of Combat Casualties

Jennifer J. Hatzfeld, Susan Dukes, and Elizabeth Bridges

ABSTRACT

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INTRODUCTION

The importance of quickly transporting combat casualties to medical care has been attributed to a French military surgeon during the Napoleonic Wars between 1792 and 1815 (Manring, Hawk, Calhoun, & Andersen, 2009). In fact, it is asserted that the improved patient outcomes noted from the organized evacuation process used by the French during the Crimean War from 1854 to 1855

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were directly responsible for the assignment of Florence Nightingale to Istanbul, Turkey, to improve the care provided to British combat casualties (Manring et al., 2009). After the development of modern aircraft, casualties began to be transported back to the United States via transport planes by the Army Air Corps in World War II, and beginning in the Korean War, the helicopter was used to transport patients from the point of injury to initial medical care, particularly when the patient's location was remote (Carter, Couch, & O'Brien, 1988). Today, combat casualties are transported in many different types of aircraft, but generally follow this same rapid evacuation approach, using helicopters at the point of injury and transport aircraft to return patients to the United States.

Advances in combat casualty care over the last several years have been consistent, determined, and truly remarkable. Perhaps, a single graph published in the *Journal of Trauma and Acute Care Surgery* (Rasmussen, Gross, & Baer, 2013) reflects this most succinctly. In the figure, the case fatality rate (CFR), which is the percentage of deaths among all combat injuries in Afghanistan, decreases steadily from 17% in late 2005 (when reliable data were available) down to 8% in 2013. Between 2007 and 2013, while the CFR continued to fall, the mean injury severity score (ISS) increased from less than 12 to greater than 14. To put this in context, an ISS from 9 to 15 is considered a "moderate" injury and associated with higher mortality rates when compared to "mild" injuries, with ISS less than 9 (Bolorunduro et al., 2011). Together, these results confirm that the decreasing CFR is not because of a larger proportion of minor injuries but because of improved survival rates for combat casualties with increasingly severe injuries. Caring for these more severely injured patients has been attributed to a "revolution" within the military medical system (Blackbourne, Baer, Eastridge, Butler, et al., 2012). But the transport of these patients within the combat zone and ultimately back to the United States, called the "en route care" system, has also required significant innovation to ensure optimal outcomes for these wounded warriors.

CURRENT EN ROUTE CARE SYSTEM

According to military doctrine (Chairman of the Joint Chiefs of Staff [CJCS], 2012), medical care within the combat casualty care system begins with first responder care where a field medic provides lifesaving interventions and calls for transport to initial medical treatment. This initial treatment is considered forward resuscitative care, which is usually provided in a temporary structure (such as a tent) and begins with damage-control surgery for traumatic injuries (Blackbourne, Baer, Eastridge, Butler, et al., 2012). From here, patients are transferred to a theater hospital, which has additional surgical and specialty capabilities, where the casualty is

either returned to duty or further stabilized before being transported to definitive care outside of the operational area (CJCS, 2012).

The en route care (ERC) system ensures that all patients are safely transported between these levels of care, while maintaining the patient's clinical condition (CJCS, 2012). As seen in Figure 3.1, casualty evacuation and medical evacuation can use multiple vehicle types, including rotary wing aircraft (helicopters), smaller fixed-wing aircraft (airplanes), boats, ships, or ground vehicles. Aeromedical evacuation (AE), or strategic evacuation, is a regulated movement that focuses on moving patients between military medical facilities using larger fixed-wing aircraft, usually from the theater hospital to definitive care (CJCS, 2012). In the most recent conflicts in Iraq and Afghanistan, this definitive care has been provided either at Landstuhl Regional Medical Center (LRMC) in Germany or one of several medical centers in the United States.

Depending on the mode of transportation, there are multiple stressors that can negatively impact the patient, including vibration, movement, and noise. However, because patients evacuated on fixed-wing aircraft are at a much higher altitude, this introduces additional physiological stressors on the injured patient. There are eight classic stresses of flight in fixed-wing aircraft, including decreased partial pressure of oxygen, barometric pressure changes, thermal changes, decreased humidity, and gravitational forces, in addition to vibration, noise, and fatigue. The combination of these physiological stresses encountered at altitude acts in a cumulative manner, and although fatigue is identified as a

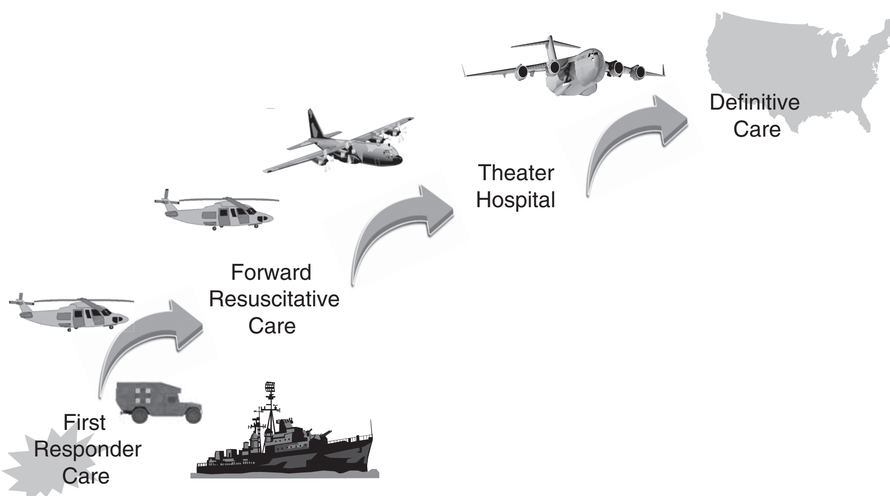

FIGURE 3.1 En route care system (CJCS, 2012).

separate stress of flight, it also is the end product of the other seven (Hickman & Mehrer, 2001).

From October 2001 until December 2011, 19,437 military personnel were medically evacuated from Afghanistan with at least one medical encounter in a fixed medical facility outside the operational theater (Armed Forces Health Surveillance Center [AFHSC], 2012b). From January 2003 until December 2011, 50,634 military personnel were also medically evacuated from Iraq followed by at least one medical encounter in a fixed medical facility outside the operational theater (AFHSC, 2012a). An analysis of the diagnoses for these military members medically evacuated from Iraq demonstrates that 17.7% (n = 8,944) were battle injury–related, with nonbattle musculoskeletal injuries a close second at 16.3% (n = 8,257). Mental disorders, including adjustment reactions, mood disorders, anxiety, and posttraumatic stress disorder (PTSD), reflected 11.6% (n = 5,892) of military members transported (AFHSC, 2012a).

Although not reflecting the military "surge" in Afghanistan in 2010, an analysis of 34,006 military personnel aeromedically evacuated from both Iraq and Afghanistan between January 2004 and December 2007 found that the most common reason for medical evacuation was musculoskeletal and connective tissue disorders (n = 8,104, 24%), followed by combat injuries (n = 4,713, 14%), neurological disorders (n = 3,502, 10%), psychiatric diagnoses (n = 3,108, 9%), and spinal pain (n = 2,445, 7%; Cohen et al., 2010). Among this group of military members, more than 22% (n = 7,675) returned to duty within 2 weeks after their evacuation (Cohen et al., 2010).

In an analysis of all patients transported by a Critical Care Air Transport Team (CCATT), which is a specialized team that provides critical care capability within AE, 2,439 patients (with 3,492 patient moves) were transported from October 2001 to May 2006 in support of military operations in Iraq and Afghanistan (Bridges & Evers, 2009). Among the 1,995 patients transported out of the operational area, battle injuries accounted for 64% of these patients (n = 1,280) and 25% (n = 504) with a noninjury, or disease, diagnosis (Bridges & Evers, 2009). Trauma patients (either because of battle injuries or nonbattle injuries) most commonly had soft tissue trauma (64%, n = 948), and 43% (n = 636) had an orthopedic injury; 69% (n = 1,034) had polytrauma, defined as having two or more areas of the body injured (Bridges & Evers, 2009).

A more in-depth analysis of 133 patients transported by CCATT from Iraq identified that 59% (n = 78) were combat trauma patients; lower extremity trauma, to include amputations, fractures, vascular injuries, and soft tissue injuries, was the most prevalent (Mason, Eadie, & Holder, 2008). The mean ISS for these CCATT patients with combat trauma was 20, with 60% of these patients having an ISS of more than 15, which is considered "severe" injury (Mason et al., 2008). Despite

the critical care capability of CCATT, some patients exceed that level of care in the ERC setting, particularly because of lung injuries and inadequate ventilation. To meet this need, an Acute Lung Rescue Team was developed and transported 24 critically ill patients out of the operational area (Fang et al., 2011).

From these descriptive studies, it becomes clear that the transport of combat casualties and the ERC system are dynamic. The patients transported reflect a wide variety of acuity levels from the most stable patients who are able to return to duty within 2 weeks to those most critically injured who require a specialized critical care team. The necessity to transport these types of patients thousands of miles around the world is itself unique and innovative. However, the dramatic changes to combat casualty care and the large proportion of patients with musculoskeletal injuries have required innovations to the nursing care provided within the ERC system to ensure the appropriate level of care is provided.

INNOVATIONS

System-Level Innovations

The development of CCATT and Acute Lung Rescue Teams, as well as a Burn Flight Team which is dedicated to transporting burn casualties, has been important to expand the level of care provided within the ERC system and decrease the amount of time it takes to move the combat casualties out of the operational area—from 21 days during the Vietnam War to an average of 28 hr during the conflict in Iraq and Afghanistan (Blackbourne, Baer, Eastridge, Renz, et al., 2012). In addition, it has been identified that the need for a higher level of nursing care during transport within the combat zone has become increasingly necessary, particularly when transporting critically injured patients on rotary-wing transport (Nagra, 2011). This need for a higher level of far forward care led to the development of the en route critical care nurse role, after it was shown that 40%–80% of flights required nurse or medical intervention during transport (Nagra, 2011). The need for flight medics with paramedic training was also established when it was identified that there were lower mortality rates for critically injured patients (ISS >15) transported by a deployed National Guard medical evacuation unit staffed by critical care-trained flight paramedics (Blackbourne, Baer, Eastridge, Renz, et al., 2012; Holland, Apodaca, & Mabry, 2013).

A physician-led medical emergency response team was developed within the British military medical system and used in southern Afghanistan, with lower mortality rates among critically injured patients compared to the traditional casualty evacuation system led by either a basic emergency medical technician or paramedic (Apodaca et al., 2013). Although it is unclear why there

is a benefit to the physician-led medical emergency response team response, it is hypothesized that earlier advanced interventions may be partially responsible for the improved survival rates, particularly among patients with ISS scores from 16 to 50 (Morrison et al., 2013). Acknowledging the need for earlier blood administration, one medical evacuation unit developed a process improvement study to evaluate the impact of providing blood products in the prehospital setting (Malsby et al., 2013). Preliminary findings suggest that this innovative approach is safe, but specific mortality outcomes have not yet been determined.

The U.S. Air Force has also developed a three-person Tactical Critical Care Evacuation Team (also referred to as "TCCET") consisting of a physician, a certified nurse anesthetist, and an emergency department or intensive care unit (ICU) nurse intended to provide critical care at the point of injury (Ricks, 2012). The current doctrine has been changed to support TCCET capability to transport patients from forward resuscitative care to theater hospitals (Vice Chairman of the Joint Chiefs of Staff, 2012), with TCCET clinicians already deployed to the combat zone who have provided critical care to these patients during transport.

Each of these innovative changes to the ERC system is dynamic and, as new evidence is identified, continues to evolve. These rapid changes, although necessary and groundbreaking, will require additional work to integrate with existing structure and clinical practices. However, these innovative practices can also be used as a model to consider in civilian trauma systems, particularly in rural areas (Bailey, Morrison, & Rasmussen, 2013).

Innovations in Spinal Immobilization

Between 2001 and 2009, among the 10,979 individuals with trauma evacuated from Iraq or Afghanistan, there were 502 individuals with spine injuries. These injuries were complex; each patient had an average of 3.7 spine injuries in addition to at least one other injury (Blair et al., 2012; Patzkowski, Blair, Schoenfeld, Lehman, & Hsu, 2012). A unique challenge in ERC is the need to safely transport patients with suspected unstable thoracolumbar spinal fractures. Although the standard of care in the United States is to secure the patients on a backboard during short transport from the site of injury to the hospital, this would not be feasible for the 8- to 10-hr transport from the theater to the U.S. military hospital in Germany. Previously, patients with unstable spinal fractures were transported on a North Atlantic Treaty Organization (NATO) litter with a 5-in. foam pad. To add rigidity, a piece of plywood was placed under the foam pad and the patients were log-rolled for pressure reduction. An innovation in the care of these patients was the introduction of the vacuum spine board (VSB) in 2009 (Mok, Jackson, Fang, & Freedman, 2013). The VSB is a bead-filled bag, which is molded around the patient. Air is then evacuated from the bag to create a hard shell, which

immobilizes the patient. During initial evaluation, which was conducted by a team of Air Force nurse scientists and clinicians, the skin interface pressure was evaluated under conditions experienced in AE, including ascent and descent from 10,000-ft cabin altitude. A unique interface between the environment and the VSB was noted. With ascent to altitude, barometric pressure decreases. To maintain the rigidity of the VSB, additional air must be removed from the device upon ascent. With descent, the vacuum pressure may need to be adjusted to account for increased barometric pressure. A concern with the use of the VSB is the increased risk for pressure ulcers because the VSB creates a rigid surface that directly molds to the body. In ground-based care, patients with spinal precautions are log-rolled to decrease sacral pressure. Although lateral rotation in the VSB is possible because of the rigid nature of the VSB, there is no reduction in skin interface pressure. This finding led to the recommendation that the VSB be released upon ascent to altitude and that the patient be log-rolled as usual. Additional padding of the heels and occiput is also recommended; however, no padding interventions were feasible for the sacrum. These guidelines were disseminated as a part of the Joint Theater Trauma System (JTTS) Clinical Practice Guideline (CPG): Cervical and Thoracolumbar Spine Injury (JTTS, 2012). To evaluate the safety of the VSB, a study was conducted to compare the incidence of pressure ulcers in 60 patients transported on the VSB compared to 30 historical controls. In the VSB group, pressure ulcers occurred in 13% of cases. There were five Stage I and three Stage II pressure ulcers, with all the Stage II ulcers on the buttocks or sacrum. This incidence was not significantly different from the 10% rate observed in the control group. In addition, there were no cases of neurological deterioration in any of the patients. In both groups, patients requiring mechanical ventilation had the highest incidence of pressure ulcers. These results demonstrate the equivalence of the VSB with the previous immobilization method on the NATO litter. Further research is needed to decrease the risk of pressure ulcers on the sacrum and buttocks while maintaining spinal immobilization and to consider other options for spinal immobilization because the VSB restricts the nursing care which can be provided for these unique patients. Research is currently ongoing to characterize risk factors for pressure ulcers among all critically ill and injured patients undergoing long-distance AE.

Innovations in Pain Management

Pain has been a significant and frequently reported symptom in Veterans of Operations Enduring Freedom and Iraqi Freedom (Gironda, Clark, Massengale, & Walker, 2006). Adverse outcomes associated with poor pain control include the development of chronic pain and PTSD. Early identification and treatment of pain are known to reduce the incidence and severity of chronic pain conditions

(Gironda et al., 2006). Effective pain management serves to decrease or modulate the potent inflammatory response resulting in hypercoagulability, multiorgan dysfunction, systemic inflammatory response, acute lung injury, traumatic brain injury (TBI), depression, and PTSD (Malchow & Black, 2008).

The Air Force mission to evacuate casualties from theater to Germany and Germany to the United States in military transport aircraft provides a unique environment in which patient pain management is crucial. Patients enter into the AE system early in the course of illness and injury treatment and recovery. During strategic fixed-wing patient transport, the stresses of flight undoubtedly contribute to pain and difficulty in communicating pain to the AE crew.

Patients evacuated back to the United Kingdom were questioned about severity of pain from point of injury back through the chain of evacuation. Two-thirds of the patients rated the pain as either moderate or severe, with the severe score indicated by 53% of those who could remember (Aldington, McQuay, & Moore, 2011). Fast and Newton (2008) reviewed the literature for pain assessment in the civilian transport environment and found little empirically based information. In a 2008 study of pain during AE from LRMC to the United States, in 120 medical and surgical/trauma patients, 27% of patients reported moderate pain (pain score 4–7 out of 10) and 11% reported severe pain (pain score 8–10 out of 10; Pfennig & Bridges, 2008). Among the subset of trauma/surgical patients ($n = 65$), 51% reported moderate pain and 9% reported severe pain. Similarly, in a study of 41 combat trauma patients being evacuated from Afghanistan to LRMC, upon arrival to the aircraft from the hospital, 33% had moderate pain and 22% had severe pain (Gentry et al., 2010). The most severe pain (8.7 ± 1.1) was in patients with orthopedic injuries with external fixators. In addition, a study conducted by Buckenmaier and colleagues (2009) of pain during AE transport used an exploratory mixed methods design which included a survey and semistructured interviews. In this study, in which patients were surveyed after being transported to LRMC in Germany, 65% reported 50% or less pain relief during transport (Buckenmaier et al., 2009). Ground transport, often a bumpy ride to and from the aircraft and medical facilities, also contributes to pain experienced by ill and injured patients.

Anesthesiologists in the military have met to institute changes to address pain needs of trauma patients (Carter, 2010). Innovative pain care strategies have been instituted during all phases of casualty care, but there are limited data on the use and impact of these strategies in the short- and long-term outcomes of patients (Clark, Bair, Buckenmaier, Gironda, & Walker, 2007). Pain management with regional anesthesia techniques has been studied at Walter Reed Army Medical Center and has been found to be safe and effective (Stojadinovic et al., 2006). Organized in 2002, the Military Advanced Regional Anesthesia

and Analgesia (MARAA) Committee is a triservice group that had a mission to develop, recommend, and implement advanced pain initiatives to be placed in the ERC environment. This group advocated for the use of continuous peripheral nerve blocks, which have been used extensively to treat isolated extremity injuries in civilian trauma. The group also advocated for use of patient-controlled analgesia and epidurals (Carter, 2010). The first successful application of a continuous peripheral nerve block on the battlefield, as described by MARAA, provided pain relief during a soldier's entire evacuation to include initial surgery and four subsequent surgeries. A peripheral nerve catheter remained in place for 16 days with no complications (Buckenmaier & Bleckner, 2008).

One of the primary advantages of preoperative regional anesthesia is the reduction of required intravenous opioid to relieve pain (Wu, Lollo, & Grabinsky, 2011). Recent research has found opioids to have some deleterious effects. The distribution of opioid receptors outside the central nervous system, such as the cells of the immune system (T cells, B cells, macrophages, etc.), indicates that opioids are capable of exerting immunomodulation (Ninković & Roy, 2013). Studies have shown that chronic opioid use can directly and indirectly suppress the immune system (Ninković & Roy, 2013). This immunomodulation could play a role in the frequency of posttrauma and postsurgical infection.

The JTTS Management of Pain, Anxiety, and Delirium in Injured Warfighters CPG (JTTS, 2013) advocates for a multimodality approach to pain therapy for injured combat casualties. Included with the more traditional intravenous narcotic pain control treatment options are epidural and peripheral nerve blocks and ketamine infusions. Low-dose ketamine infusions have been found to have a profound analgesic effect with minimal side effects. Ketamine binds the *N*-methyl-D-aspartate receptor and decreases the total dose of narcotics needed to treat a patient (JTTS, 2013).

Beginning in 2011, the U.S. Air Force Air Mobility Command initiated a policy establishing guidelines which allow patients with epidural analgesia and peripheral nerve blocks to move through the ERC system under the management of AE crew members and aeromedical staging facility personnel. Although pain management in the AE environment has received the attention of the military medical community and advancements have been made in management, the characterization of pain assessment, management, effectiveness, and outcomes have not been studied. Accurate pain assessment is a necessary precursor to effective pain management. However, pain assessment can be challenging in polytrauma patients, especially in those with severe head injury, cognitive impairment, and multiple wounds (Clark, Scholten, Walker, & Gironda, 2009). The environment of the aircraft adds additional difficulties to the assessment and documentation of pain.

Recently, a prospective assessment of real-time ratings of pain acceptability, intensity, and satisfaction of patients was conducted on AE missions from Ramstein Air Field, Germany, to Andrews Air Force Base (AFB), Maryland (Dukes, Bridges, McNeill, et al., 2013). A sample of 114 U.S. military personnel with injuries transported by AE on flights between December 2012 and May 2013 participated. Acceptable pain intensity was a median of 6/10 (range 2–9), with 76% of patients indicating an acceptable pain intensity greater than 4. During AE transport, 75% of patients reported at least one pain score of 4 or more, with the highest pain scores occurring upon arrival at the aircraft (4.3 ± 2.3), suggesting the need for interventions to safely optimize pain management during this handoff period.

In an effort to capture the environmental factors and social context impacting pain management in AE, an ethnographic study was also conducted onboard AE missions from Ramstein, Germany, to Andrews AFB, Maryland (Hatzfeld, Serres, & Dukes, 2013). Data collection was conducted during eight missions throughout 2013. The results of this study highlighted the need to have a coordinated effort through the ERC system, recognizing the need for preparatory guidance on pain management given to patients while they are still in the aeromedical staging facilities. This study also confirmed the commitment of both AE crew members and aeromedical staging facility personnel to helping patients manage pain. One particular area for interventions to further improve en route pain management is to overcome barriers to communication during transport.

Systems and human factors engineering approaches are also being used to document and assess pain management in the AE system. Human factors engineering considers the interactions of the environment, people, technologies, processes, information, and flow to improve system processes, performance, and safety. Preliminary results suggest pain management might be improved by implementing enhanced information sharing practices and enhanced system monitoring and feedback loops, streamlining and redesigning documentation, and expanding and supplementing procedures for patient flight preparation.

As we explore pain in the ERC system from various disciplines and begin to understand the AE patient's pain experience, innovative nonpharmacological means to treat pain in the ERC environment are also being pursued. Battlefield acupuncture is one such intervention that has been evaluated in the ERC environment. Battlefield acupuncture, which consists of acupuncture to the ear, was shown to be a feasible technique to be performed within the ERC system. Patients reported an average pain rating of 4.07 before battlefield acupuncture and pain scores 1-hr posttreatment and postflight of 2.17 and 2.76, respectively ($p < 000.1$; Burns et al., 2013).

Innovations in Monitoring

In the study of 2,439 casualties evacuated by CCATT in support of Operation Enduring Freedom and Operation Iraqi Freedom between 2001 and 2006, 69% of the casualties suffered polytrauma (Bridges & Evers, 2009). The complexity of these injuries is further highlighted in an analysis of 1,151 combat casualties, who had 3,500 surface wounds and 12,889 injuries, with an average of 11.2 injuries per casualty (Champion et al., 2010). Recently, there has been an increased incidence of complex dismounted blast injuries, where the casualty has suffered traumatic amputations of at least two extremities with or without pelvic and perineal blast involvement. In 63 combat casualties with complex blast injuries (137 amputations), the casualties received an average of 19.5 ± 18.2 (range 0–104) units of packed red blood cells (PRBCs; Fleming, Waterman, Dunne, D'Alleyrand, & Andersen, 2012). The ability to care for these complex patients in the austere and demanding ERC environment is challenging, particularly for those casualties who are stabilizing but may not be stable. Because of these complex injuries, there is a need for innovative use of technologies to enhance the ability to detect occult hemorrhage and the onset of hypoperfusion, guide therapies such as fluid volume resuscitation, and evaluate the patient's response because these critically injured casualties move across the care continuum.

Monitoring a patient's physiological status, detection of deterioration, and the response to therapies is based traditionally on standard vital signs (heart rate, blood pressure, oxygen saturation). A series of studies conducted by the U.S. Army Combat Casualty Research Program found that standard vital signs may remain unchanged in the face of impending cardiovascular collapse (Convertino & Ryan, 2007), and they failed to identify patients who required lifesaving interventions or to differentiate between patients with severe trauma who survived or died (Convertino et al., 2008). In contrast to vital signs, less invasive or noninvasive physiological parameters have been found to be potentially useful in monitoring and guiding therapy for patients at high risk for hemodynamic compromise.

Noninvasive Monitoring

Functional hemodynamic indicators, which include ventilator-induced variations in the amplitude of the arterial blood pressure or pulse oximeter waveform (pleth variability index [PVI]), are accurate indicators of a patient's ability to respond to a fluid bolus with an increase in stroke volume (Bridges, 2013; Marik, Cavallazzi, Vasu, & Hirani, 2009; Sandroni et al., 2012). However, the use of arterial-based measurements in ERC may be limited because not all patients have invasive monitoring. The Masimo Rainbow SET/Radical-7 Pulse Co-Oximeter, which is a noninvasive pulse oximeter, provides a continuous functional

hemodynamic indicator (PVI) and total hemoglobin (SpHb). However, no studies had used this noninvasive monitoring method to describe the physiological status of severely injured combat casualties undergoing resuscitation. As an example of an innovation in care, a study of 24 critically injured combat casualties (ISS; 21 ± 10) who were admitted to two U.S. Military Role III trauma hospitals in Afghanistan was conducted to describe their physiological status during resuscitation across the emergency room, operating room, and ICU continuum. The patients' physiological status was described using standard vital signs, invasive and noninvasive functional hemodynamic indicators, and continuous hemoglobin (Bridges, 2011, 2012).

In a subset of 15 patients who had greater than 60 min of monitoring in the ICU, the PVI was significantly correlated with arterial-based functional hemodynamic indicators, and it was a sensitive and specific indicator of fluid responsiveness. The PVI was significantly higher in fluid responders versus nonresponders (23.0 ± 9.0 vs. 11.6 ± 2.8; $p < .001$), and a PVI threshold of 16 or more had a sensitivity of 86%, specificity of 94%, and an area under the curve of 0.93 (95% confidence interval [0.87–1.00]) to predict fluid responsiveness. These findings are important because they may aid in tailoring resuscitation to avoid the administration of fluids to a patient who is a nonresponder. In this case, if the patient is hypoperfused, alternative therapy such as a vasoactive medication may be needed. An important finding in this study was that changes in the PVI preceded clinical deterioration (Figure 3.2), which may provide an early warning sign of impending compromise. Although the PVI was an accurate predictor in the ICU setting, it was not useful in the operating room because of the frequent administration of vasoactive medications, continuous transfusions, and surgical stimulation.

Trending of SpHb has also been found to be useful in monitoring physiological status in trauma and surgical patients (Applegate et al., 2013; Baulig et al., 2013; Berkow, Rotolo, & Mirski, 2011; Miller, Ward, Shiboski, & Cohen, 2011). In the same study of the 24 combat casualties, the SpHb was not precise enough to replace the laboratory hemoglobin value (SpHb-Coulter Hb bias 0.3 ± 1.6 g/dl; 95% limits of agreement −2.8, 3.4 g/dl); however, continuous SpHb accurately detected acute changes in hemoglobin and identified critical decreases which were not detected by intermittent laboratory measurements. In 14 cases, one or more clinical events (systolic blood pressure [SBP] <90 mmHg, mean arterial pressure <60 mmHg, PRBC given) occurred, and in 6 out of 14 cases, the SpHb decreased >10% or 1 g/dl before the clinical event. In the case presented in Figure 3.2, the SpHb did not increase despite the administration of three units of PRBCs, suggesting that the transfusions were likely replacing ongoing blood losses. In addition, the increase in the PVI (suggesting a decrease in preload

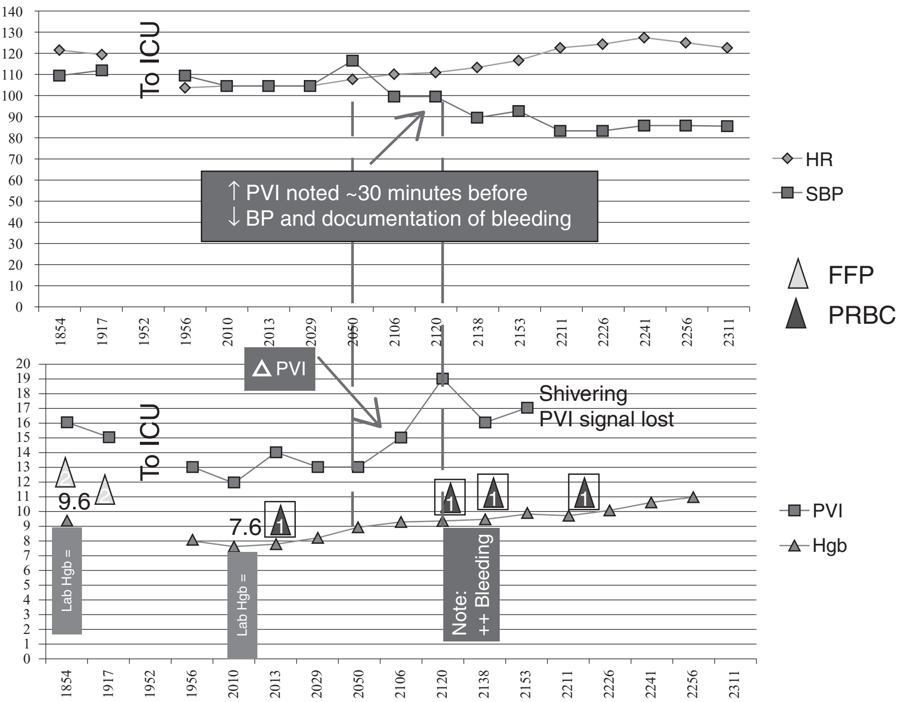

FIGURE 3.2 Physiological status of a combat casualty with injuries caused by an improvised explosive device. Injuries include a right leg below the knee amputation, left leg above the knee amputation, right arm fracture, puncture wounds on the buttocks and perineum, a scrotal injury, and right femoral neck fracture. The patient was admitted to the emergency department in a coagulopathic state. In the emergency department, the patient received four units of FFP. The decision was made to resuscitate the patient in the ICU with a surgical procedure to follow. In the ICU, the patient received one unit of PRBCs at 2,010 for a hemoglobin of 7.6 g/dl. The SpHb increased to approximately 9 g/dl after the transfusion. At 2,120, the patient was noted to be exsanguinating from his left leg amputation (HR = 110 bpm; SBP = 100 mmHg). The patient received three units of PRBCs over a 60-min period without a significant change in the SpHb (note that no laboratory hemoglobin was obtained). Also of note, the PVI started to increase at 2,050, which was approximately 30 min before a change in vital signs or blood loss was noted. (Abbreviations: ICU = intensive care unit; PVI = pleth variability index; BP = blood pressure; HR = heart rate; SBP = systolic blood pressure; FFP = fresh frozen plasma; PRBC = packed red blood cell; Hgb = hemoglobin)

because of hemorrhage) occurred approximately 30 min before the documentation of the blood loss and almost 1 hr before significant changes were noted in the vital signs. Together, these additional parameters may provide earlier identification of occult deterioration. Although this study describes the patients' physiological status while they move across the resuscitation continuum in a fixed

facility, there have not been any published studies describing continuous SpHb monitoring or noninvasive functional hemodynamic monitoring to further characterize the patients' physiological status as they move across the medical evacuation or AE phases of the ERC continuum.

Monitoring Perfusion Status

The ability to monitor a patient's perfusion status to detect hypoperfusion and evaluate the response to therapy is integral to shock resuscitation. However, perfusion indicators that are available and feasible in the operational environment, such as base deficit (BD) or lactate, are intermittent. Skeletal tissue oxygen saturation (StO_2 <75%), which is obtained using noninvasive near-infrared spectroscopy, has been found to predict the development of organ dysfunction and outcomes in severely injured trauma victims (Cohn et al., 2007; Moore et al., 2008). The StO_2 measurement is obtained using a probe placed on the thenar eminence or forearm. A pilot study in 13 trauma patients demonstrated the feasibility of StO_2 monitoring in the prehospital setting, even when other vital signs could not be obtained (Lyon, Thompson, & Lockey, 2013). In 150 civilian trauma patients, although the absolute prehospital StO_2 did not predict the need for lifesaving interventions, changes in the StO_2 in response to a vascular occlusion test were associated with severity of injury and mortality (Guyette et al., 2012). In a laboratory study involving the creation of central hypovolemia using lower body negative pressure, skeletal muscle oxygen saturation decreased during the first stage of the creation of central hypovolemia, in contrast to vital signs, which were late indicators of impending cardiovascular collapse (Soller et al., 2012). The use of StO_2 has been described in the military setting. In severely injured combat casualties, the StO_2 tracked with resuscitation efforts (Beilman & Blondet, 2009) and predicted which patients would require a blood transfusion despite having "stable" vital signs (Beekley et al., 2010). All of these studies demonstrate the frequency of occult hypoperfusion in trauma patients and the potential benefit of additional perfusion monitoring to detect this occult state and to guide therapy. A limitation of these previous studies is that the measurements were obtained at a single fixed location.

Given the rapid transport and need to maintain the highest level of care across the care continuum, it is important to understand the incidence of occult hypoperfusion as the combat casualties move from point of injury through transport and resuscitation at forward resuscitative care and theater hospitals. In an ongoing study being conducted in Afghanistan, intermittent vital signs and indicators of perfusion status (BD, lactate, and StO_2) are being measured in seriously injured combat casualties at the forward resuscitative care setting immediately before and after transport to theater hospital (Bridges & Beilman,

2013). In preliminary analysis of these data, hypoperfusion was present in 13 of 24 patients, with 6 patients in a severe state of shock and 6 with occult hypoperfusion. In two cases, the StO_2 was also less than 75%, which is consistent with a state of hypoperfusion. The case in Table 3.1 provides an example of a critically injured patient with occult hypoperfusion (BD = −12, StO_2 73%) despite aggressive resuscitation. In addition, despite relatively "normal" vital signs, the patient's condition may have deteriorated during the transport phase, as indicated by the worsening of the StO_2 (BD = −11, StO_2 62%).

A unique finding in this study, which is exemplified in Table 3.2, is the presence of hypoperfusion in three casualties with normal vital signs but a markedly elevated StO_2 (>90%). The increased StO_2 may suggest a shunt state or failure of oxygen use at the level of the mitochondria. The implications of this abnormal perfusion state were described in a pilot study of 10 seriously injured trauma patients (Burggraf & Waydhas, 2009). In 3 patients who had an initial StO_2 level greater than 85%, two developed multisystem organ failure (MOF) and 1 died. In 3 patients with an StO_2 level less than 75% on admission, 1 patient developed MOF and subsequently died. In contrast, no patients with a normal StO_2 (75%–85%) developed MOF or died. Further data collection is ongoing, with analysis focusing on absolute StO_2 values, as well as changes in StO_2 values pre- and posttransport and the incidence of hypoperfusion in the presence of an abnormally elevated StO_2. These results may inform future

TABLE 3.1

Example of Hypoperfusion and an Abnormally Low StO_2 in a Casualty Who Suffered a Gunshot Wound to the Arm, Abdomen, and Thigh

Vital Sign	Forward Resuscitative Care (pretransport)	Theater Hospital (posttransport)
HR (bpm)	60	104
BP (mmHg)	178/103	188/88
SaO_2 (%)	99	99
StO_2 (%)	73	62
Hgb (g/dl)	18	19
BD	−12	−11

Note. The patient underwent emergent damage control surgery (splenectomy, nephrectomy, and repair of soft tissue injuries) and received 12 units of packed red blood cells, 8 units of fresh frozen plasma, and 6 units of whole blood. The patient was hypothermic (93.3°F) despite warming. Pretransport vital signs were obtained 6.5 hr after injury and flight time was approximately 30 min. HR = heart rate; bpm = beats per minute; BP = blood pressure; SaO_2 = arterial oxygen saturation; StO_2 = skeletal tissue oxygen saturation; Hgb = hemoglobin; BD = base deficit.

TABLE 3.2

Casualty Who Fell Approximately 50 ft and Suffered a Mandibular Laceration, Bilateral Hemothorax/Pneumothorax, and an L1/L2 Vertebral Fracture

Vital Sign	Forward Resuscitative Care (pretransport)	Theater Hospital (posttransport)
HR (bpm)	102	93
BP (mmHg)	102/63	118/84
SaO_2 (%)	100	100
StO_2 (%)	100	58
Hgb (g/dl)	6	10
BD	−10	−5

Note. The casualty received 6 units of packed red blood cells (PRBCs) and 6 units of fresh frozen plasma (FFP) during the initial resuscitation. Preparation for transport from the Role II hospital was approximately 2 hr after the injury; 35 min elapsed between the pretransport and posttransport vital signs. During the transport, the patient received an additional 2 units of PRBCs and 2 units of FFP. HR = heart rate; bpm = beats per minute; BP = blood pressure; SaO_2 = arterial oxygen saturation; StO_2 = skeletal tissue oxygen saturation; Hgb = hemoglobin; BD = base deficit.

research integrating continuous StO_2 monitoring during transport and characterizing the microvascular perfusion state under cases where there is an abnormally increased StO_2.

IMPLICATIONS FOR FURTHER INNOVATION, RESEARCH, AND POLICY

In military operations in Iraq and Afghanistan, explosive blast has been, and continues to be, the most common wounding etiology, earning TBI the title of the "signature injury" of the conflict in Iraq (Hoge et al., 2008). TBI patients who survive the primary trauma are highly susceptible to secondary insults to the injured brain. These secondary insults are a delayed, physiological response to the primary injury and associated with worse outcomes (Chestnut et al., 1993). The austere ERC environment poses challenges to the monitoring and care of patients with TBI, and the stresses of flight can potentially contribute to secondary neurological insults (Fang, Dorlac, Allan, & Dorlac, 2010; Goodman et al., 2010). A study was conducted of secondary insults (e.g., hypotension, hypoxia, hyperthermia, hypothermia, hyperglycemia, and hypertension) which occurred in patients with severe TBI who were evacuated from Iraq or Afghanistan from 2003 to 2006 (Dukes, Bridges, & Johantgen, 2013). This study found that hyperthermia was the secondary insult documented most frequently, with 47%

of the patients suffering at least one episode of an increased temperature. In addition, 25% of the patients suffered from hypoxia at some point from the point of injury to arrival back in the United States. A study by O'Connell, Littleton-Kearney, Bridges, and Bibb (2012) identified that secondary insults of hypothermia and hypoxemia after TBI increased the odds of 24-hr mortality. These studies help provide a better understanding of secondary insults in patients with TBI in the unique ERC environment. Innovative preventive or protective measures are needed to contribute to improved outcomes for these combat casualties.

Closed-loop technology is another emerging capability within health care because it allows clinicians to focus on multiple priorities while patients are maintained at a safe equilibrium (Arney et al., 2010). This innovation may be particularly helpful in the transport environment, when clinicians may be unable to monitor and respond to patients at certain points during flight, such as takeoff and landing and during turbulence. The prospective study of pain during fixed-wing flight from LRMC to Andrews identified that the mean time from "wheels up" (or takeoff) to cruising altitude, when it is safe for crew members to remove their seatbelt and attend to a patient, was 39 ± 33 min, but this restricted period lasted as long as 131 min in at least one flight (Dukes, Bridges, McNeill, et al., 2013). This unique care environment demonstrates the necessity and potential value of closed-loop technology within the ERC system, especially for ventilation and sedation. Further research and regulatory approvals will be needed to establish the reliability of closed-loop technology in this dynamic setting, and policies will need to be changed to incorporate this future innovation.

CONCLUSION

The ERC setting is an essential part of combat casualty care, and providing nursing care in this unique environment is both challenging and dynamic. System innovations, as well as innovations to provide spinal immobilization, adequate pain management, and technology to monitor patient status, have demonstrated improved outcomes and continue to increase the survival rates for these wounded warriors. Further refinement of these innovations and additional analysis of clinical data are essential to capture the full benefits. However, continued innovations are needed in the future, particularly to understand the secondary insults for complex injuries such as TBI and closed-loop technology. With the termination of military operations in Iraq and the anticipated conclusion of military operations in Afghanistan, the numbers of combat injured are expected to diminish. The ERC clinicians, researchers, and leaders will need to ensure that these innovations are institutionalized and future innovations keep pace with the rapid pace of discovery.

DISCLAIMER

The views expressed in this chapter are those of the authors and do not necessarily represent the official position or policy of the Air Force, the Department of Defense, or the U.S. government.

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